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Optimization of grid connected conventional energy resources by using single phase micro inverter with LCL filter

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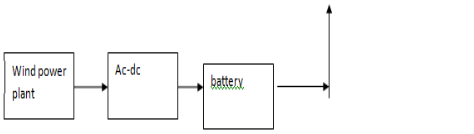
Abstract— A Photovoltaic (PV) system's power output is not constant and fluctuates depending on weather conditions. Fluctuating power causes frequency deviations in the power utilities when PV power penetration is large.Using a battery is the common practice to smooth PV output power fluctuations. In this paper, we propose and simple fuzzy based control method for PV-diesel hybrid system to reduce frequency deviations without smoothing PV output power fluctuations. By means of the proposed method, output power control of PV system considering the conditions of power utilities and maximizing energy capture are achieved.This paper presents a low cost high efficiency transformer isolated micro-inverter for single-phase grid connected photovoltaic (PV) system. The proposed micro inverter is composed of two stages, an isolated dc-dc converter stage and an inverter stage with a dc link. A high frequency transformer isolated high voltage gain boost half-bridge dc-dc converter is used at the first stage to achieve maximum power point tracking (MPPT) and to step up the PV voltage to the high voltage dc-link. A pulse width modulated (PWM) full-bridge inverter with LCL filter is used at the second stage to output the synchronized sinusoid current with unity power factor to the grid. By utilizing the transformer leakage inductance, two primary side switches can achieve zero voltage switching (ZVS). A 210 W prototype of the proposed micro-inverter has been built and tested. The efficiency of the proposed boost half-bridge dc-dc converter has been measured according to the PV curve, which is up to 98.2%. Experimental results are provided to demonstrate the validity and features of the proposed circuit.

Keywords : Frequency deviations; Fuzzy reasoning; PVoutput power fluctuations; Maximum PV power; OPC server, RSLogix 5000 Fuzzy Designer;

I. INTRODUCTION

Mitigating the possibility of global warming is of great interest worldwide. The consumption of fossil fuels must be reduced and clean and renewable energy sources must be introduced. Among various renewable energy systems, photovoltaic power generation systems (PV systems) are expected to play an important role as a clean power electricity source in meeting future electricity demands. However, the power output of PV systems fluctuates depending on weather conditions, season, and geographic location. In the future, when a significant number of PV systems will be connected to the grids of power utilities, power output fluctuation may cause problems like voltage fluctuation and large frequency deviation in electric power system operation [1], [2]. To date it has not been necessary for PV generators to provide frequency regulation services to the power system. In the future, with an increasing penetration of PV generation, their impact upon the overall control of the power system will be significant [3]. This will lead a situation where the PV generators will be required to share some of the duties,such as frequency control. Therefore, for the penetration of large

conventional Block diagram



PV system's output power in the utility without reduction of the reliability of utility power systems,suitable measures must be applied to the PV systems side.Statistical smoothing of power delivered to utilities has been reported in [4]. However, it is not helpful to reduce the real output power fluctuations and frequency deviation. Moreover, it is a statistical approach rather than a technical approach. On the PV system side, batteries can be used as smoothing device for a PV system's output.There have been investigations aimed at improving the performance of PV systems equipped with batteries [5]- [8]. However, the additional cost of batteries is a barrier to the large scale installation of PV systems. In addition, used batteries must be disposed of without causing environmental problems. On the other hand, these investigations focused on peak power generation problem, load management, and outage attributes of PV power generation system. They have not given any emphasis on reduction of frequency deviation. Smoothing of PV system output by tuning MPPT control is demonstrated in [9]. In this method, when the insolation increases rapidly, the operating MPPT point changes to a new point where the maximum power is not generated with the current insolation. It was reported that this method can be applied to several PV power generation systems to achieve a combined output power fluctuations smoothing. However, the condition of power utilities like frequency deviation is not considered for tuning the MPPT and for limiting the new output voltage. All of these methods tried to smooth the fluctuating PV power. However, none of them give emphasis on controlling the PV power according tofrequency deviation. Therefore, these methods have no sharing of the duties like frequency regulation. In this paper, we propose a new fuzzy based PV power control method to reduce frequency deviations. This method uses fuzzy reasoning [10], [11] to produce output power command and it has three inputs, which are frequency deviation, average insolation and change of insolation. Here, the output power command is decreased in time when frequency deviation is negative. On the other hand, output power command increases when frequency deviation is positive. Hence, it is possible to control the output power command corresponding to power system condition by the proposed method. The proposed method is compared with the method where maximum available power is always fed to the utility. The simulation results using the actual detail model of PV generation system show the effectiveness and feasibility of the proposed method to reduce frequency deviation to deliver PV power near maximum PV power.

Wind power

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electrical power,windmills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. Large wind farms consist of hundreds of individual wind turbines which are connected to the electric power transmission network. Offshore wind farms can harness more frequent and powerful winds than are available to land-based installations and have less visual impact on the landscape but construction costs are considerably higher. Furthermore, offshore poses problems when considering accessibility for maintenance issues. Small onshore wind facilities are used to provide electricity to isolated locations and utility companies increasingly buy surplus electricity produced by small domestic wind turbines.

Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation and uses little land.[2] The effects on the environment are generally less problematic than those from other power sources. As of 2011, Denmark is generating more than a quarter of its electricity from wind and 83 countries around the world are using wind power on a commercial basis.[3] In 2010 wind energy production was over 2.5% of total worldwide electricity usage, and growing rapidly at more than 25% per annum. The monetary cost per unit of energy produced is similar to the cost for new coal and natural gas installations.

Wind power is very consistent from year to year but has significant variation over shorter time scales. The intermittency of wind seldom creates problems when used to supply up to 20% of total electricity demand,[5] but as the proportion increases, a need to upgrade the grid, and a lowered ability to supplant conventional production can occur.[6] Power management techniques such as having excess capacity storage, geographically distributed turbines, dispatchable backing sources, storage such as pumped-storage hydroelectricity, exporting and importing power to neighboring areas or reducing demand when wind production is low, can greatly mitigate these problems.[7] In addition, weather forecating permits the electricity network to be readied for the predictable variations in production that occur

II. ISOLATED POWER SYSTEM

The concept of isolated power utility used in this paper is shown in Fig. 1. The isolated power utility consists of the diesel generator and PV system that generates power to supply the demand. In addition, it is assumed that the isolated power utility is always operated independently. The isolated power system model which consists of diesel generator, PV power generation system and load is shown in Fig. 2[19] where *Si* is the insolation, * *Pinv* is the command power generated by output power command system, *PA* is the generated power by PV power generation system, *Pd* is generated power by diesel generators, *R* is the speed regulation, *Tg* is the governor time constant, *Tt* and *Tr* are the time constants, *PL* is the load, *M* is the inertia constant, *D* is the damping constant, and Δf is the frequency deviation of small power utility. As a frequency control method of power system, flat frequency control method which is used in majority of small power system is adopted. In Fig. 3[19], PV power generation system including solar array, inverter and PI controller is shown where *VA* is the solar array voltage, *IA* is the solar array current, Δf is the frequency deviation, *Vs* is the generated supply voltage by the inverter, *Is* is the generated supply current by the inverter, and *Ii*nv* −□*Iinv* is the error between command current and produced current. The control algorithm for the inverter [12] adopted here is very simple. The inverter output voltages and currents are sensed and transformed from 3-phase to synchronously rotating 2- phase. The command currents are generated dividing the output power command by sensed inverter voltage. Then the error between command inverter current and actual inverter current is processed through a PI controller to generate the PWM pulses. For maximum power extraction, the output power command is generated by maximum power point tracking algorithm. For simple structure and less costly implementation, a Perturbed and Observed (P&O) [13] algorithm was chosen in the present structure. As the design of power converter and the control system is significantly influenced by the solar module characteristics, these will briefly reviewed here. The solar module is a nonlinear device and can be represented as a current source model, as shown in Fig. 4. The traditional *I-Vψ* characteristics of a solar module are given by the following equation [14]:

Recently, because of the energy crisis, the renewable energy sources, such as wind turbine, photovoltaic (PV) panels, etc. become more and more popular in industrial and residential applications. With different radiance and temperature, the dc output voltage and the maximum output power of the PV panel will change. So, an inverter interface with maximum power point tracking (MPPT) is required for the PV panel to connect to the grid. There are three popular technologies for the PV panels connected to the grid through an inverter: centralized three-phase inverter for matrix connected PV panels, single-phase string inverter for series connected PV panels and modular integrated micro-inverter for a single PV panel [1-9]. Due to its low cost and high reliability, modular integrated micro-inverter is preferred for the future application [3, 4]. Based on the galvanic isolation, the PV inverter topologies can be divided into transformer-less topologies and transformer isolated topologies. Since the output voltage of a single PV panel is as low as 20~50 V, a high voltage gain inverter is required for the PV panel to connect to the single-phase grid. Although the transformerless inverter topologies have low cost and high efficiency features, they usually do not have enough voltage gain to boost the input voltage. Therefore, the transformer isolated inverter topologies with high voltage gain are preferred for a single PV panel grid-connected application. For the transformer isolated inverter topologies, there are two popular approaches. The first approach utilizes the single stage flyback inverter or isolated buck-boost inverter, which is able to replace the electrolytic capacitor with high voltage low capacitance film capacitor for the energy storage [10-18]. This approach usually uses less switches with low cost, the high frequency transformer is the major design issue for these topologies to achieve high efficiency. The second approach is a two stage approach with a transformer isolated dc-dc converter as the first stage and a full-bridge inverter as the second stage [19-27]. A high efficiency dc-dc converter with soft switching is usually designed for the first stage [4, 26]. A full bridge inverter with PWM or line frequency switches is usually used for the second stage. The dc-dc converter in the first stage is the major design issue to achieve low cost and high efficiency. A low cost and high efficiency ZVS bidirectional dc-dc converter with boost type half-bridge input side has been proposed for the fuel cell and battery applications [28-30]. Compared to the traditional half-bridge dc-dc converter, this converter have continuous input current and reduced transformer turns ratio features which is especially suitable for the step up applications [31-38]. The literatures mainly concentrate on the bidirectional topologies using active switches on both primary and secondary side. This paper presents a boost half-bridge micro-inverter for single-phase photovoltaic system applications with low cost and high efficiency features. The proposed inverter consists two stages, the transformer isolated boost half-bridge dc-dc stage and the full-bridge PWM inverter stage. The two active switches voltage doubler in the secondary side of the traditional bidirectional boost half-bridge dc-dc converter [28] are replaced with two diodes, since only single directional power flow is needed in the proposed micro-inverter system. Only two active switches are utilized in the boost half-bridge dc-dc converter, and no dc current flow into the transformer like the flyback converter, which reduce the total system cost and increase the system efficiency. The two switches are controlled complementarily, and the duty cycle determined by the input voltage generated by MPPT and the desired low dc link voltage. When the transformer leakage inductance is large enough, ZVS of these two active switches can be achieved. A PWM full-bridge inverter is used at the second stage to output the synchronized sinusoid grid current. In the following sections, the circuit description and basic operation principles will be first discussed. Then, the soft-switching operation principle of the boost half-bridge dc-dc converter will be discussed. The system control strategies and design guideline will be provided after that. Simulation and experimental results will be provided to demonstrate the validity and features of the proposed circuit. The efficiency curve of the boost half-bridge dc-dc converter is measured according to the input PV panel power versus voltage curve with peak efficiency up to 98.2%.

Figure 3. PV power generation system.

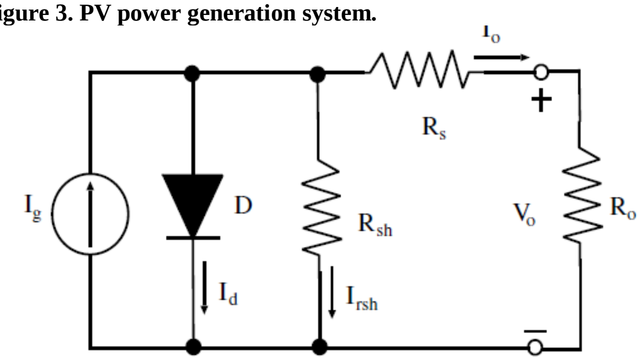


Figure 4. Equivalent circuit of a solar module.

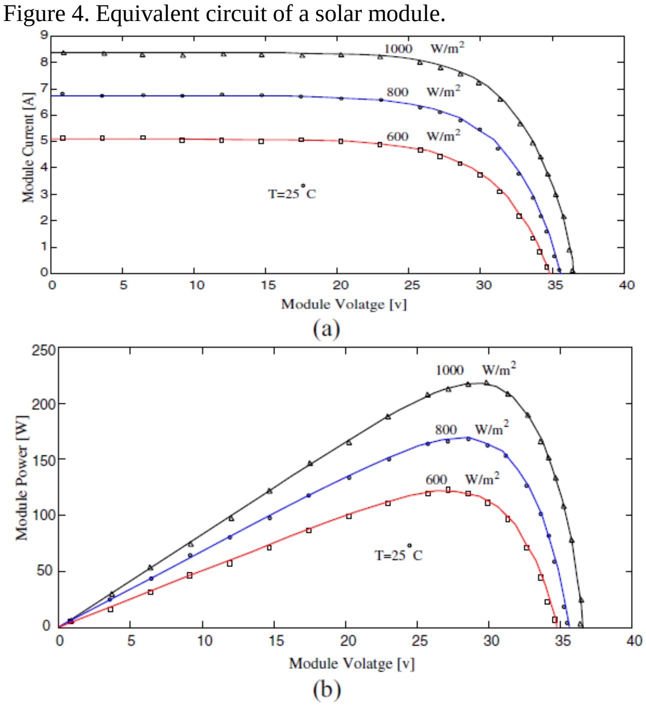
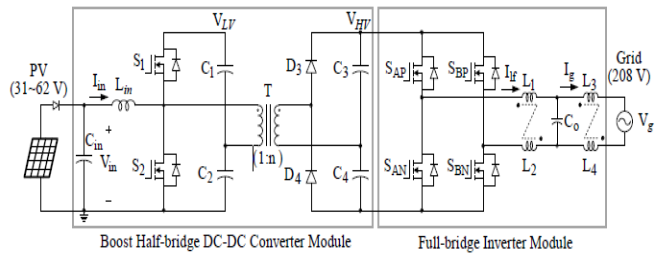
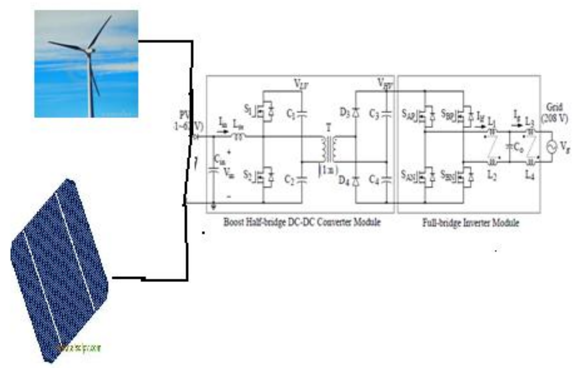


Figure . Solar module characteristic curves. (a) Current-voltage curves. (b) Power –voltage curves. The discrete data points shown are taken from the manufacturer's curves [15], and show excellent correspondence with the model.

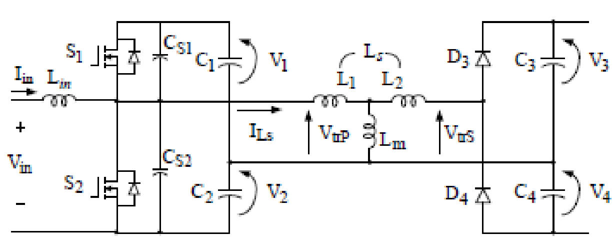
II. **PROPOSED CIRCUIT DESCRIPTION AND OPERATING PRINCIPLE**





Proposed system circuit

Fig. shows the proposed boost half-bridge micro-inverter main circuit structure. The proposed circuit is composed of two stages with a real high voltage dc-link. A boost halfbridge isolated dc-dc converter is used in the first stage to cover the input voltage range and achieve the MPPT function of PV panel. A full-bridge PWM inverter with a LCL filter is used in the second stage to controSince the output voltage of a single PV panel with 72~80cells is about 31 ~ 62 V, which is much lower than the singlephase grid voltage, a high voltage gain step-up dc-dc converter is required. Due to the high voltage gain and residential application safety requirement, the isolated dc-dc converter using a high-frequency transformer is one of the solutions. Forthe isolated dc-dc converters, several topologies candidates including flyback, forward, half-bridge and full-bridge can be considered. Although flyback converter has only one active switch with relatively low cost, the flyback transformer and preferred discontinuous operation may increase the converter power loss. The forward converter only utilizes a half wave rectifier with reduced the output voltage, is more suitable for step-down application. The full-bridge converter utilizes four active switches, which is more suitable for high power (> 1kW) application. In the low power (around 200 W) micro inverter application, the full-bridge dc-dc converter solution may increase the total system cost. Traditional half-bridge dcdc converter can be considered as a buck converter in thel the current to the grid. Forthe first stage, it can be considered as a boost converter with the output capacitor splitted into two capacitors C1 and C2. Cin and Lin represent the input capacitor and inductor of the traditional boost converter respectively. The switch S1 and S2 are two MOSFETs and are controlled in a complementary manner, and the duty cycle is determined by the low dc-link voltage VLV and the input voltage Vin. By controlling the input voltage, the MPPT of the PV panel can be achieved. The low dc-link voltage VLV has to be set higher than the maximum output voltage of PV panel to ensure the boost operation of the circuit. The transformer T primary side is connected between the center tapes of the switches S1 and S2 and the capacitor C1 and C2. The voltage-second of this transformer is always zero during one switching period, no dc-current will flowing into this transformer. A voltage doubler composed of two diodesD1 and D2 and two capacitors C3 and C4 is connected on the secondary side of the transformer. The high voltage dc-link voltage VHV is the sum of the voltage of C3 and C4. The transformer turns ratio is 1:n is the voltage ratio of the low dc link voltage and the high dc-link voltage which is VLV: VHV. The secondary stage full bridge inverter is composed of four MOSFETs (SAP, SAN, SBP, SBN) with SPWM control strategy. Grid current Ig is controlled as a sinusoid waveform with unity power factor through third order LCL filter (L1 ~ L4, and Co).The inductors L1 and L2 are winded in one core, and so do the inductors L3 and L4primary side, and the transformer primary side voltage is only one half of the input voltage, which makes it more suitable for the voltage step-down application. At the same time, the sever voltage overshoot across the secondary side diode also limits the application of full-bridge and half-bridge with high output voltage. Generally speaking, the dc-dc converter topologies with a voltage fed primary side are more suitable for the voltage step-down application with high input voltage and low output voltage such as communication power supply. The dual structure of the above voltage-fed dc-dc converter is the current fed dc-dc converter with inductors or boost type input structure are more suitable for the voltage step-up applications [25, 39]. However, the dual circuit of the traditional voltage fed half-bridge dc-dc converter or double-L dc-dc converter suffer server voltage overshoot problem across the primary side switches. Complicated clamping circuits are required to limit the primary switch voltage overshoot, which increase the total cost and reduce the system reliability [25]. The proposed boost half-bridge dboth primary side active switches and the secondary diodes, which can eliminate the voltage spike across the switches by proper circuit layout. Different from the traditional voltage-fed symmetrical half-bridge dc-dc converter with duty cycle control, the two switches of the proposed boost half-bridge converter is controlled complimentarily. The transformer is fully utilized at both switching periods to transfer the energy. If the leakage inductance of the transformer is designed small enough; the leakage inductance current is almost square waveform with minimum rms value. In this way, the copper loss of the transformer and the switching device conduction loss can be minimized. In the meanwhile, if the leakage inductance of the transformer is designed relatively large, the energy stored in the leakage inductance can also be used to achieve the zero voltage switching of the primary side devices. The proper design and selection of the transformer leakage inductance should be a trade off with different application. Fig. 2 shows the primary referrer equivalent circuit of the boost half-bridge dc-dc converter. The transformer is replaced by its equivalent circuit with two leakage inductance L1 and L2 a magnetizing inductance Lm. The leakage inductance is used to transfer the energy from the primary side to the secondary side. Different from the bidirectional boost half-bridge dc-dc converter using the phase shift of the primary side switch and the secondary switch, the secondary diode of the proposed topology will conduct automatically when the transformer primary side voltage VtrP is higher than the secondary side voltage VtrS. The energy can only transferred from the primary side to the secondary side, so the referred voltage of the secondary side V3 and V4, will always smaller than V1 and V2. CS1 and CS2 are the parasitic capacitance of MOSFETs S1 andc-dc converter has capacitors across the



III. SOFT-SWITCHING OPERATION PRINCIPLES OF THE DCDC CONVERTER MODULE

When the leakage inductance is large enough, the ZVS of the first stage boost half-bridge dc-dc converter can be achieved with the proper selection of deadtime. In this section, the ZVS operation of the first stage boost half-bridge dc-dc converter will be analyzed and discussed. In order to simplify the circuit analysis, the primary referred equivalent circuit is drawn in Fig. 2 is used for analysis, where the transformer is replaced with a leakage inductance and a magnetizing inductance. Fig. 5 shows the commutation steps in one switching cycle. Fig. 6 shows the idealized waveforms and switching time in one switching cycle.

1) (t1 ~ t2): The circuit is in steady state, the switch S1 isconducted, the diode D3 is conducted, the energy istransferred from the primary side to the secondary side, as shown in Fig. 5(a).

2) (t2 ~ t3): At t2, the switch S1 is turned off, the leakage inductance begin to resonant with the switch parasitic output capacitor CS1 and CS2, since these two capacitors can be selected big enough to make the charge of the capacitor CS1 long enough than the switch S1 turn off time, the zero voltage turn off of the switch S1 can be achieved. The leakage inductor continues to discharge the capacitor CS2 until the voltage across this capacitor drop to zero, as shown in Fig. 5(b).

3) (t3 ~ t4): At t3, the capacitor CS2 voltage drop to zero, and the parasitic diode D2 of switch S2 is conducted naturally as shown in Fig. 5(c).

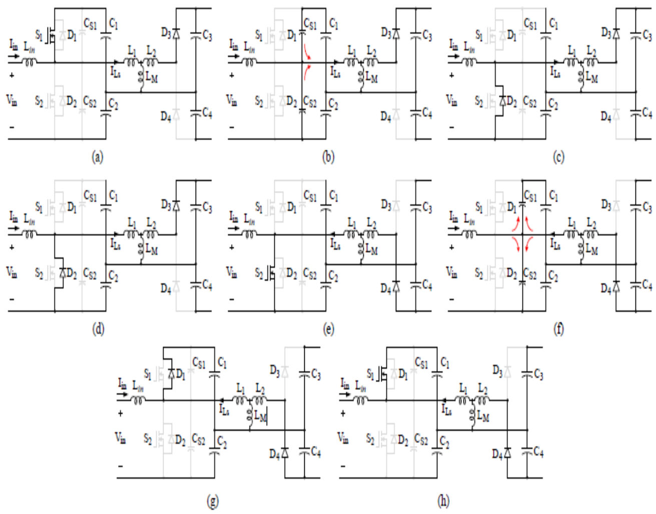
4) (t4 ~ t5): At t4 switch S2 can be turned on at zero voltage, since the body diode has already conducted. The secondary diode current begin to change from D3 to D4, as shown in Fig. 5(d).

5) (t5 ~ t6): At t5 diode D3 is turned off completely, and diode D4 begin to conduct, the circuit enter into another steady state as shown in Fig. 5(e). During this period,the energy is transferred from the primary side to the secondary.

6) (t6 ~ t7): At t6 the switch S2 is turned off, the output capacitor CS1 of the switch S1 begin to discharge while the output capacitor CS2 of the switch S2 begin to charged by the input current and the transformer current ILs. The switch S2 is turned off at zero voltage as shown in Fig. 5(f).

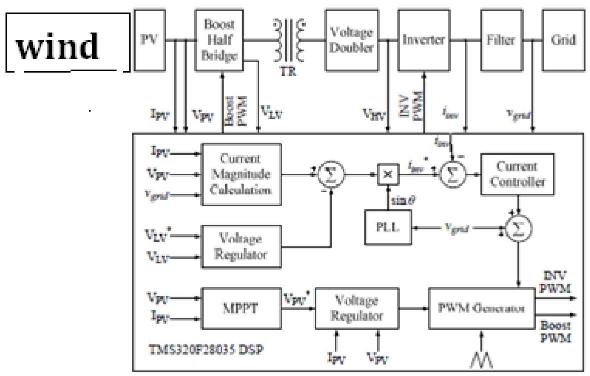
7) (t7 ~ t8): At t7 the capacitor CS1 voltage is discharged to zero, the parasitic diode D1 of the switch S1 is turned on naturally.

8) (t8 ~ t9) At t8 the top switch S1 can be turned on with zero voltage switching since the diode D1 has already conducted. From t9 the next switching cycle begins,which is the same as the time t1. If the parasitic capacitance of the MOSFETs S1 and S2 is not big enough, a relatively large capacitor has to be added in parallel with the switch to ensure the zero voltage turn off.The zero voltage turn on of the bottom switch S2 is determined by the current in the leakage inductance, when the load is light or the leakage inductance is not big enough, zero voltage turn on cannot be achieved. Since the energy stored in the leakage inductance should be larger than the energy stored in the capacitor CS2. And the capacitor CS1 is discharged by the input current and the transformer leakage inductance current at the same time. So the zero voltage turn on of the top switch S1 can be achieved easier than the bottom switch S2. With light load or small leakage inductance, the ZVS of these two switches cannot be achieved, the boundary condition will be derived and discussed in the future paper due to the page limitation.



Commutation step diagrams during a switching cycle

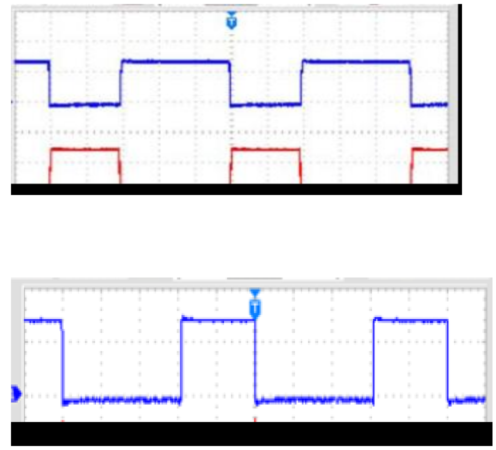
Controlediagram



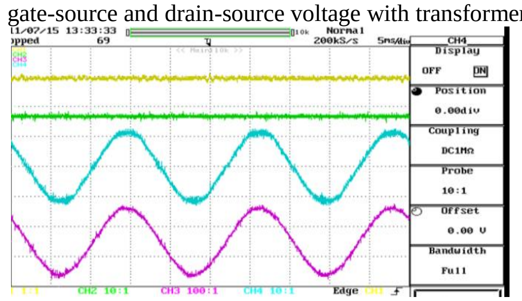
Maximum power point tracking

Maximum power point tracking (MPPT) is a technique that grid-tie inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels,[1] though optical power transmission systems can benefit from similar technology.[2] Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.[3] MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

Experimental results

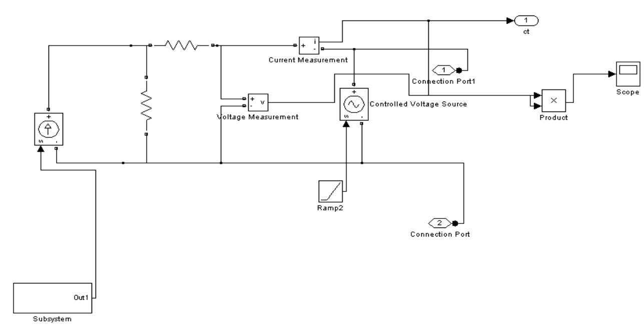


complimentary gate drive voltage of the primary two switches. (b) S2 gate-source and drain-source voltage with transformer current

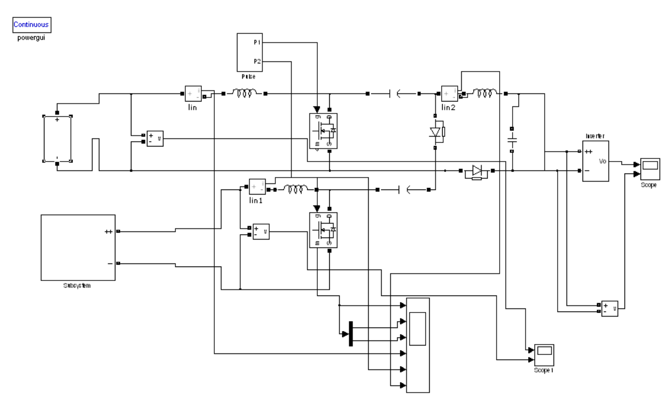


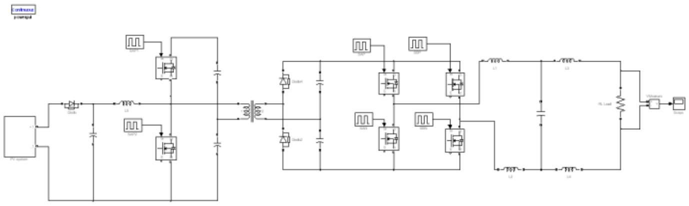
Input voltage, current, and the output voltage current waveforms

Simulation results

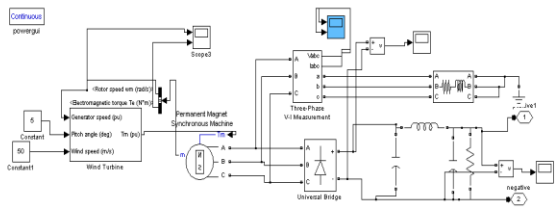


Pv cell eqvelent diagram In simulation

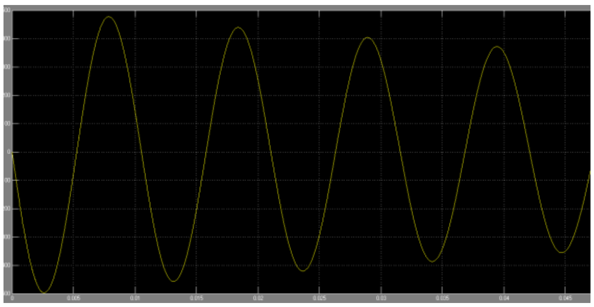




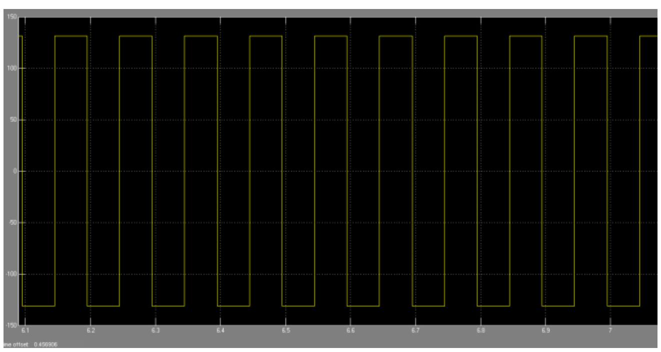
Proposed circuit simulation diagram



Wind simulation diagram



Grid   current



Grid voltage

CONCLUSION

A simple, however robust system was presented in this work, to be used with electrical energy generated by photovoltaic modules. The system does not need batteries since it operates connected to the grid. The energy supply occurs in periods where the sunlight is present, being the system in wait state when it does not have light. An immediate application for this type of system can be made in places that need refrigeration due to the heat produced for the sun, for example, in air-conditioning system, where it has coincidence between the demand of energy for refrigeration and the generation of electric energy by the photovoltaic system. A low cost and high efficiency boost half bridge dc-dc converter is proposed and analyzed. By using this topology with capacitors across all the active switches and diode, the voltage overshoot problem can be eliminated. The transformer is utilized fully to transfer energy with pure ac current, which can be designed with high efficiency. By utilizing the transformer leakage inductance, the ZVS of the primary switches can be achieved.